National Aeronautics and Space Administration

Radiative Heat Transfer Modeling in Fibrous Porous Media

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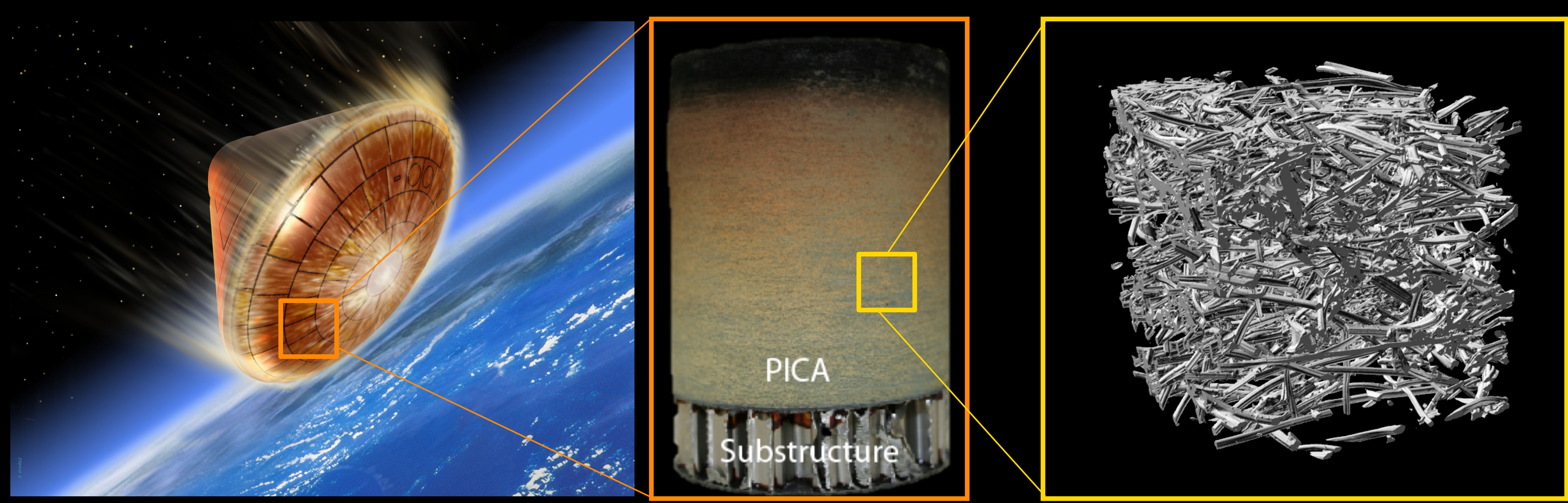
Background



Volume rendering of FiberForm micro-CT

Phenolic-Impregnated Carbon Ablator (PICA) was developed at NASA Ames Research Center as a lightweight thermal protection system material for successful atmospheric entries. The objective of the current work is to compute the effective radiative conductivity of fibrous porous media, such as preforms used to make PICA, to enable the efficient design of materials that can meet the thermal performance goals of forthcoming space exploration missions.

Ablator Modeling

Conduction + Radiation = Total heat transfer

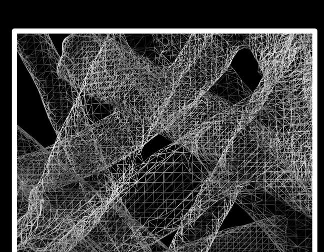
An efficient and MPI parallel procedure is developed to first obtain relevant view-factors using a collision based Monte-Carlo method and second to compute the final steady-state radiative heat flux [1]. The radiative conductivity computed can be combined with the value calculated for thermal conductivity using PuMA [2], a NASA software for extracting porous material properties, to determine the total effective conductivity from the intrinsic conductivity of constituting phases.

$$q'' = -[k_c + k_r]\nabla T$$

Methods

Finding the View Factors

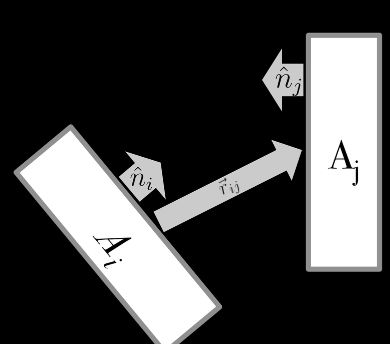
The view factor, F_{ij}, between surfaces i and j, where A_i and A_j are the areas of the surfaces, are defined in the equation below. A view factor equal to zero implies that two surfaces cannot "see" each other, or in other words, a light ray emitted by one of the surfaces cannot reach the other surface.



Triangulation of the fibers (~30 million triangles)

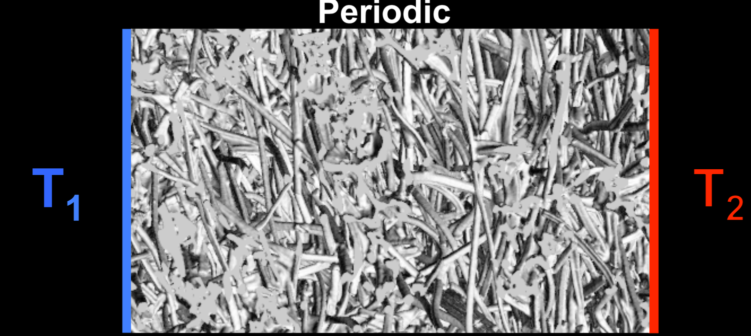
Method: The input geometry is first triangulated into discrete surfaces. For each surface i:

1. A large number of rays are projected outward to uniformly sample the angle space nearby.
2. Each voxel passed through by a ray is interrogated to see if it contains any emitting surfaces for which to calculate the corresponding view factor, using the equation below.
3. Lastly, when all rays for surface i are processed, another surface is chosen and steps 1-3 are repeated.



$$F_{ij} = \frac{1}{A_i}\int_{A_i}\int_{A_j}\frac{|\hat{n}_i\cdot\hat{r}_{ij}||\hat{n}_j\cdot\hat{r}_{ij}|}{|\vec{r}_{ij}|^2}dA_j dA_i$$

Heat Transfer Calculation



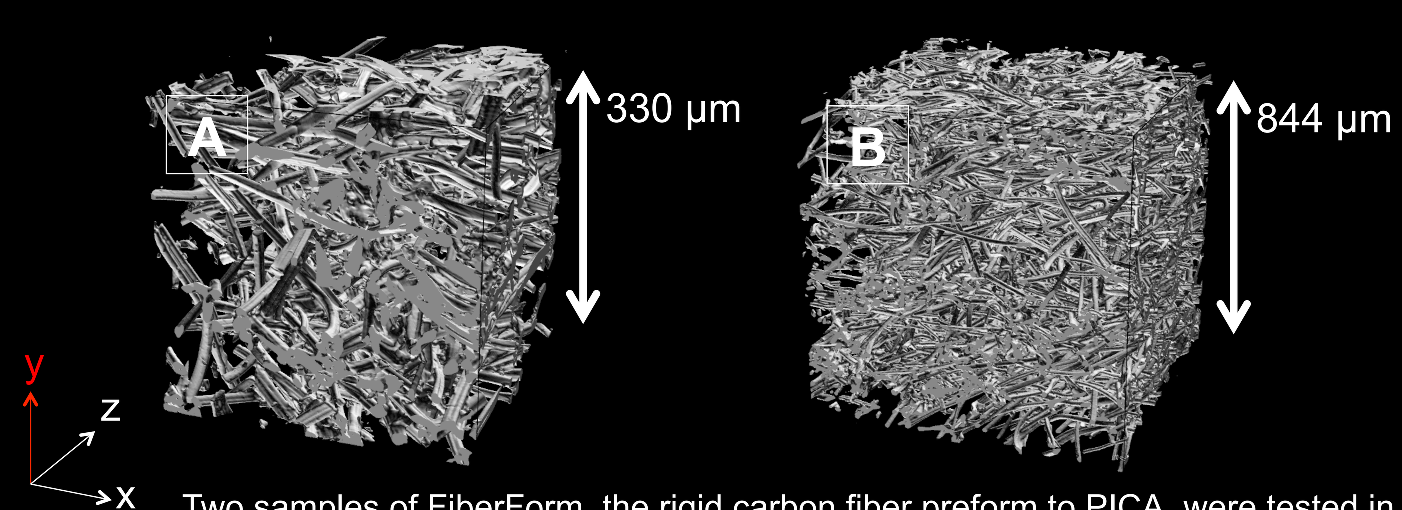
The view factors data generated is used calculate the radiative heat transfer in a certain domain. The radiosity J_i, or total heat flux leaving a surface, is computed with the equation below. As this constitutes a large sparse coupled linear system, an iterative process is used to solve for the radiosity of each surface between walls 1 and 2:

$$J_i = \epsilon_j \sigma T_j^4 + (1-\epsilon_j)\sum_j F_{ij}J_j$$

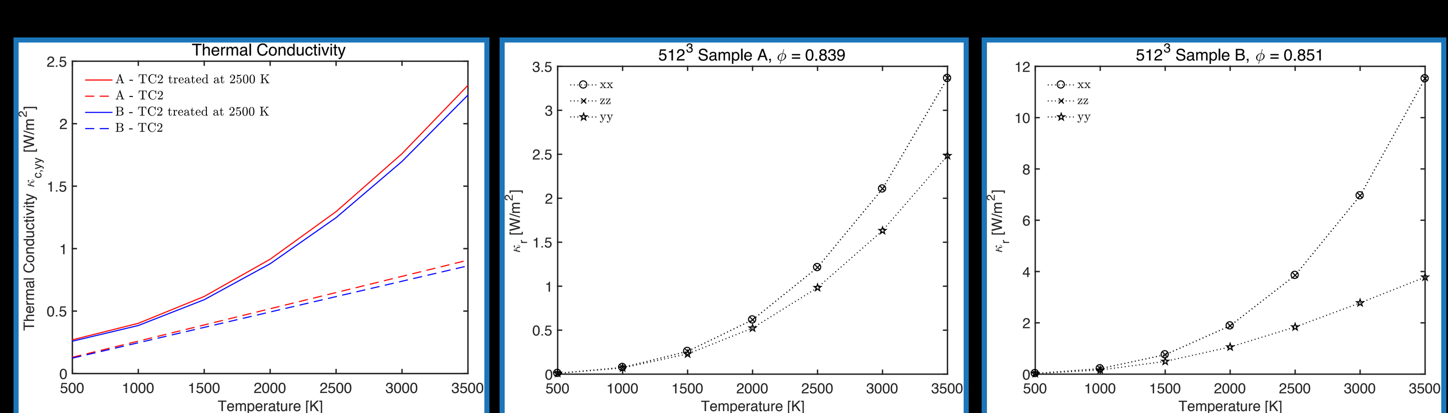
where ε is emissivity and T_j is the local temperature. This computation assumes that each surface is isothermal, diffuse, and opaque. The output is the net axial heat flux, averaged over the other two directions.

Results Conclusions

Using PuMA to render a digital representation of the sample, the radiative heat transfer in the carbon fiber preform is investigated. For the results shown, a temperature gradient of 1K is imposed in the axial direction, resulting in a finite net heat flux.



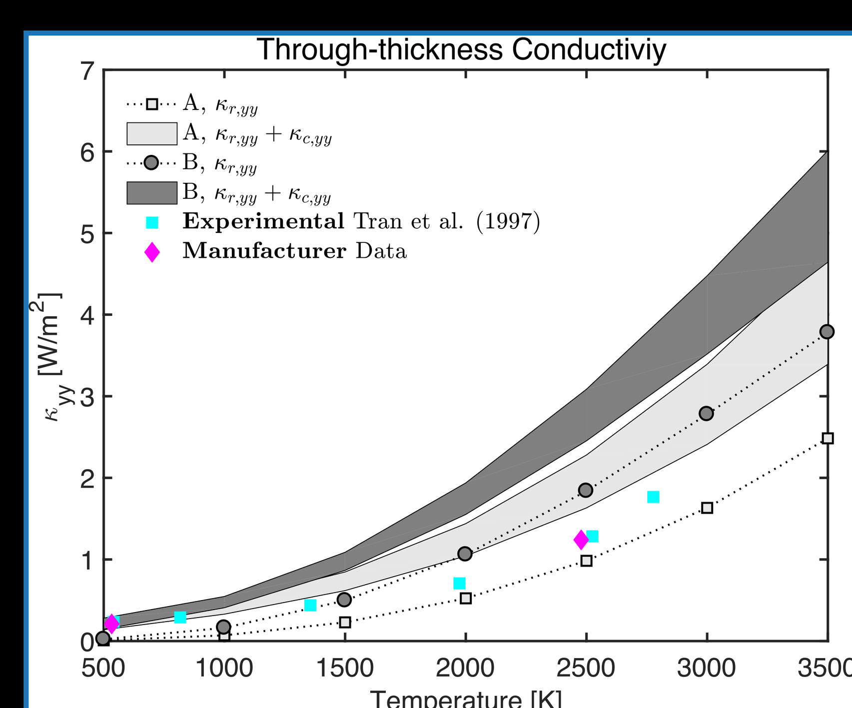
Two samples of FiberForm, the rigid carbon fiber preform to PICA, were tested in this study, each acquired from tomography data at voxel resolution 0.65 µm for Sample A and 1.65 µm for Sample B.



a b c

The dataset of radiosity, which is computed at each solid voxel, is first cleared of outliers, which are the void voxels, then fitted using a robust least squares fitting method. The difference between the radiosities at the two ends of the domain as well as the temperature difference imposed between them, are used to compute the effective conductivity [3].

a) Using two different values for the carbon conductivity, corresponding to TC2 and TC2 heat-treated at 2500K [4], the total thermal conductivity of FiberForm in N_2 is computed using PuMA.
b-c) Radiative conductivity of samples A and B, with porosities Φ_A=0.839 and Φ_B=0.851, in the 3 principle directions. Anisotropy of the thermal behavior of carbon fiber preform is confirmed.



Effective conductivity in the through-thickness direction for Samples A and B compared to experimental and manufacturer data. The variability is due to the uncertainty in thermal conductivity of the carbon fibers. The total conductivities predicted illustrate the dependence on carbon fiber density and porosity. Since the experiments are for lower density preforms (160kg/m³) and the computation is done on higher density samples (~183.6 kg/m³), the total conductivity predicted is higher than those of the experiment.

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